SnapShot: Key Numbers in Biology

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Cell size

- **Bacteria (E. coli):** ~0.7-1.4 μm diameter, ~2-4 μm length, ~0.5-5 μm^2 in volume; 10^4-10^5 cell/μl for culture with OD₆₀₀=1
- **Yeast (S. cerevisiae):** ~3-6 μm diameter, ~20-160 μm^3 in volume
- **Mammalian cell volume:** 100-10,000 μm^3; HeLa cell: 500-5000 μm^3 (adhering to slide ~15-30 μm diameter)

Length scales inside cells

- **Nucleus volume:** ~10% of cell volume
- **Cell membrane thickness:** ~4-10 nm
- **“Average” protein diameter:** ~3-6 nm
- **Base pair:** 2 nm (D) x 0.34 nm (H)
- **Water molecule diameter:** ~0.3 nm

Concentration

- **Concentration of 1 nM:** in E. coli ~1 molecule/cell; in HeLa cells ~1000 molecules/cell
- **Characteristic concentration for a signaling protein:** ~10 nM-1 μM
- **Water content:** ~70% by mass; general elemental composition (dry weight) of E. coli: ~C₄H₇O₂N₁; Yeast: ~C₆H₁₀O₃N₁
- **Composition of E. coli (dry weight):** ~55% protein, 20% RNA, 10% lipids, 15% others
- **Protein concentration:** ~100 mg/ml = 3 mM.
- **Total metabolites (MW < 1 kDa):** ~300 mM
- **Diffusion-limited on-rate for a protein:** ~10^-6-10^-7 M^-1 s^-1 for a protein substrate of concentration ~1 μM the diffusion-limited on-rate is ~100-1000 s^-1 thus limiting the catalytic rate k_cat

Energetics

- **Membrane potential:** ~70-200 mV → 2-6 k_BT
- **Free energy (ΔG°) of ATP hydrolysis under physiological conditions:** ~40-60 kJ/mol → ~20 k_BT/molecule ATP; ATP molecules required during an E. coli cell cycle ~10^-10 ^x 10^-7
- **ΔG° resulting in order of magnitude ratio between product and reactant concentrations:** ~6 kJ/mol = ~60 meV = 2 k_BT

Diffusion and catalysis rate

- **Diffusion coefficient for an “average” protein:** in cytoplasm D ~ 5-15 μm^2/s → ~10 ms to traverse an E. coli → ~10 s to traverse a mammalian HeLa cell; small metabolite in water D ~ 500 μm^2/s

Genome sizes and error rates

- **Genome size:** E. coli = 5 Mbp; S. cerevisiae (yeast) = 12 Mbp; C. elegans (nematode) = 100 Mbp; D. melanogaster (fruit fly) = 120 Mbp; A. thaliana (plant) = 120 Mbp; M. musculus (mouse) = 2.6 Gbp; H. sapiens (human) = 3.2 Gbp; T. aestivum (wheat) = 16 Gbp
- **Number of protein-coding genes:** T. aestivum (wheat) = 40,000; S. cerevisiae = 6000; C. elegans, A. thaliana, M. musculus, H. sapiens = 20,000
- **Mutation rate in DNA replication:** ~10^-8-10^-9 per bp
- **Misincorporation rate:** transcription ~10^-4-10^-5 per nucleotide translation ~10^-4-10^-5 per amino acid

Useful biological numbers extracted from the literature. Numbers and ranges should only serve as “rule of thumb” values. References are in the online annotated version at www.BioNumbers.org. See the website and original references to learn about the details of the system under study including growth conditions, method of measurement, etc.
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Biological processes are becoming increasingly quantifiable. Taking stock of key numbers in cell and molecular biology enables back-of-the-envelope calculations that test and sharpen our understanding of cellular processes. Further, such calculations provide a quantitative context for the torrent of data from new experimental techniques. However, such useful numbers are scattered in the vast biological literature in a way that often leads to a frustrating literature-mining ordeal. Here, we provide a set of basic numbers in biology that we find extremely useful for obtaining an order of magnitude feel for the molecular processes in cells. Several examples (see below) show how to combine these numbers to think about biological questions. The values should be considered rules of thumb rather than definitive values as variety is the spice of life and variability is ever present in biology.

Is There Enough Time to Replicate the Genome?

The bacterium Escherichia coli has a genome of roughly 5 million base pairs (bp) and a replication rate in the range of 200–1000 bp/s. These numbers imply that it should take two replisomes at least 2500 s to replicate the genome, a number that is much larger than the maximal division rate of ~20 min. How can this be? It turns out that, under ideal conditions, E. coli uses nested replication forks that begin to replicate the DNA for the granddaughter and great granddaughter cells before the daughter cells have even completed replication.

How Many Mutations in a 5 ml Culture of Bacteria?

Using the $10^{-12}$ mutation rate of E. coli per replication and a genome size of $\sim 10^{8}$ (both strands), we predict $\sim 10^{7}$ mutations per genome replication. In a 5 ml saturated culture (optical density ~2.0) of E. coli, there are about $10^{12}$ to $10^{14}$ cells. The final doubling of this culture requires the replication of $\sim 10^{14}$ cells, thus even this last cell division event would be responsible for $\sim 10^{8}$ single base pair substitutions. If the culture started with a single bacterium, every single nonlethal base pair substitution in the E. coli genome is likely to be represented in the culture.

How Long to Reach Confluence?

In a 96 multiwell plate, each well has a diameter of 5 mm (i.e., an area of $20 \times 10^2 \mu m^2 = 2 \times 10^4 \mu m^2$). Given that the diameter of a HeLa cell is $25 \mu m$ (i.e., $500 \mu m^2$ area), it takes roughly 40,000 cells to reach confluence. Starting with a single cell (obtained by cell sorting rather than cell splitting) with a generation time of about 1 day, the time to reach confluence is about 2 weeks.

How “Dense” Is a Saturated E. coli Culture?

A saturated E. coli culture has about $10^9$ cells/ml. Given that each cell is about $10^{-12}$ grams, we get a cell concentration of about 1 mg/ml or about 1 part in a thousand of the mass (or volume). The mean spacing between the cells is roughly $10 \mu m$ (which is not as dense as the concentration of bacteria in the gut of the termite where densities are typically a factor of ten higher).

How Many Carbon Atoms Are in a Cell?

A cell with a volume of 1 $\mu m^3$ and a density of about 1 g/ml has a total mass of $10^{-12}$ grams. From the formula C$_7$H$_{12}$O$_2$N, and the weights of the elements, we derive a carbon content of about $12 \times 4/(12 + 4 + 7 + 2 + 16 + 14) = 48/101$ or about half of the dry mass. With 30% dry mass (70% water), we obtain $\sim 10^{-11}$ gm of carbon. Next we transformed the number of molecules using Avogadro’s constant: $6 \times 10^{23} \times 10^{12}/12 = 5 \times 10^4$ carbon atoms per cell. To verify this, we have done the calculation in a different way: assuming there are about $3 \times 10^8$ proteins, each one consisting of about 300 amino acids, we get a total of $\sim 10^8$ amino acids. An amino acid has about five carbon atoms, so we arrive at a similar value. Both estimates depend linearly on the cell volume, which can vary significantly based on growth conditions.

How Far Can Macromolecules Move by Diffusion?

It takes about 10 s on average for a protein to traverse a HeLa cell. An axon 1 mm long is about 100 times longer than a HeLa cell, and as the diffusion time scales as the square of the distance it would take $10^2$ seconds or $\sim 2$ days for a molecule to travel this distance by diffusion. This demonstrates the necessity of mechanisms other than diffusion for moving molecules long distances. A molecular motor moving at a rate of $1 \mu m/s$ will take a “reasonable” time (15 min) to traverse an axon 1 mm in length.

ACKNOWLEDGMENTS

We thank Uri Alon, Niv Antonovsky, Danny Ben-Zvi, Erez Dekel, Idan Efroni, Avigdor Eldar, Yuval Eshed, Nir Friedman, Hernan Garcia, Paul Jorgensen, Michal Kenan-Eicher, Jane Kondev, Marc Kirschner, Avi Levy, Michal Lieberman, Elliot Meyerowitz, Elad Noor, Dave Savage, Maya Schuldt, Eran Segal, Benny Shilo, Guy Sigal, Rotem Sorek, Mike Springer, Bodo Stern, Arbel Tadmor, Rebecca Ward, Detlef Weigel, Jon Widom, and Tall Wiegel for help in preparing this SnapShot.

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